Hubble Space Telescope
On-orbit Disturbance Characterization
and Ground to On-orbit Comparisons

J. W. Sills Jr.
Lockheed Martin Technical Operations
Greenbelt, MD. 20770

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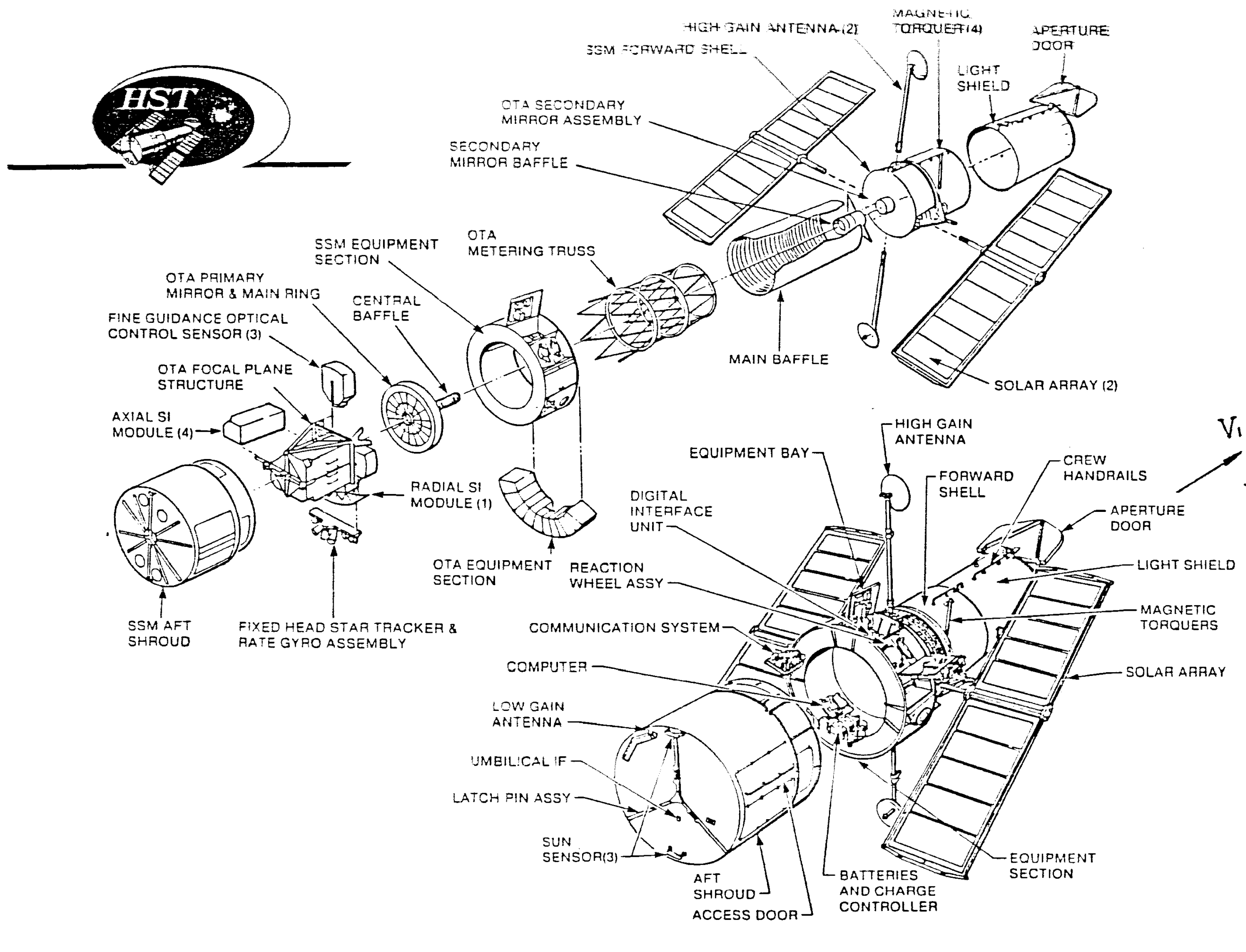
Lockheed Martin Missiles & Space

AGENDA

- **Overview of HST and Solar Arrays**
- **Solar Array Disturbances, SA1 and SA2**
  - **On-orbit Characteristics**
  - **Potential Sources of Excitation**
  - **Analysis Results**
  - **Feathering Test Results**
- **Ground/On-Orbit Test Comparisons**
  - **On-orbit Jitter Testing**

HST LAYOUT



Exploded View of the Hubble Space Telescope

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FLEXIBLE SOLAR ARRAY LAYOUT

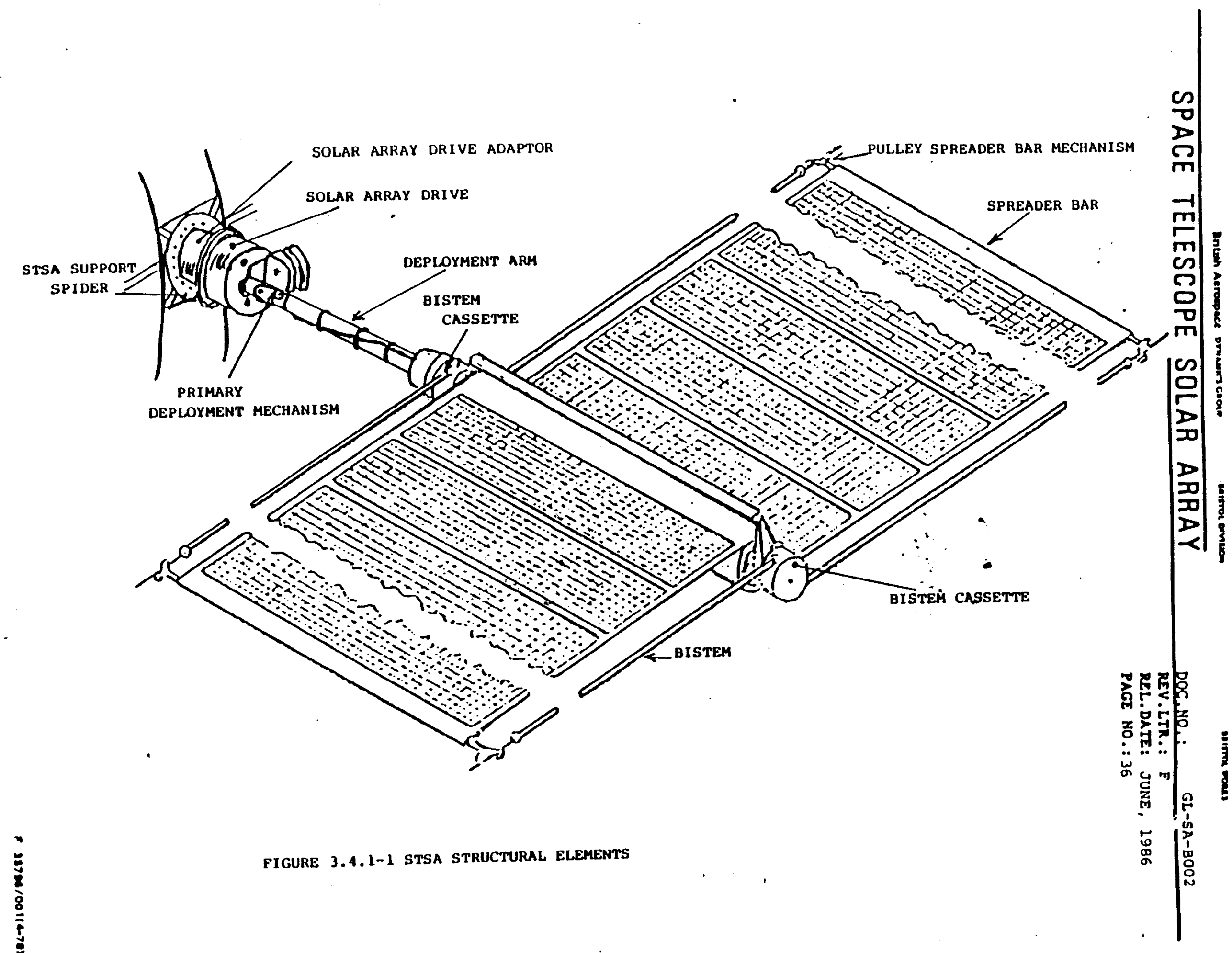

FIGURE 3.4.1-1 STSA STRUCTURAL ELEMENTS

HST ON-ORBIT DISTURBANCE CHARACTERIZATION HISTORY

- The HST was deployed in April of 1990. Since the initial deployment Orbital Verification, multiple on-orbit engineering tests have been conducted to characterize the HST dynamics.
- Efforts post deployment focused primarily on identifying and understanding the source of unwanted jitter
- These efforts led to corrections in the flexible SA design which were implemented during the first Servicing Mission (SM1)
- Multiple characterization tests including SA Feathering Tests, On-orbit transfer function tests, and On-orbit jitter tests were implemented to further understand the dynamics of the on-orbit disturbances.
- These characterization tests primary focus were to identify the fundamental in-plane and out-of-plane responses of the flexible SA1 and SA2 such that modifications could be made to the existing control system to provide proper attenuation of disturbances.

HST POST DEPLOYMENT NOMINAL CHARACTERISTICS

- **Nominal expected dynamic characteristics occur during portions of the latter half of the Orbital day and during most of the Orbital night.**
- **Peak vehicle rotation rates are on the order of 0.1-0.2 arc-seconds/second.**
- **The dominant response frequencies (italicized values represent the largest contributor) about each axis with the +V3 HST axis oriented toward the sun are:**

  V1: ***0.113-0.115*, 1.26, 1.4 Hz during the day***

  ***0.112-0.117*, 0.64-0.65, 1.3-1.4 Hz during the eclipse**

  V2: ***0.12*, 0.39, 1.0 Hz during the day***

  ***0.10-0.104*, 0.35, 1.0 Hz during the eclipse**

  V3: **0.11-0.12, 0.62, *1.2-1.4* Hz during the day***

  0.10, 0.117, *0.64-0.66* Hz during the eclipse
- **Response with respect to Solar Array orientation varies, with the 0.1 Hz frequencies about the V1 and V3 axes the most sensitive.**
- **The overall rotational response has been predicted as being one to twoorders of magnitude over budget.**

* **The daytime response characteristics were taken from 14 minute based PSD's which included an arbitrary number of daytime anomalies.**

HST POST DEPLOYMENT
TRANSITION TO DAY CHARACTERISTICS

- **The event occurs within one to two minutes after orbital sunrise.**
- **The overall magnitude is 1- 2 arc-second/second.**
- **The dominant response frequencies (italicized values represents the largest contributor) about the HST axes with the +V3 axis oriented toward the sun are:**

  – **VI: 0.096- 0.10, *0.107-0.109*, 0.75, 1.4 Hz**

  – **V2: *0.111-0.112*, 0.37, 0.75, 1.0 Hz**

  – **VI 0.096- 0.10, 0.34, 0.38, *0.63-0.64*, 0.66-0.68 Hz.**

- **Response with respect to Solar Array orientation varies, with the 0. 1 Hz frequencies about the V1 and V3 axes the most sensitive.**
- **The overall rotational response magnitude is predicted to be 2 to 3 orders of magnitude over budget.**

HST POST DEPLOYMENT
TRANSITION TO NIGHT CHARACTERISTICS

- **The event occurs within one to two minutes after eclipse.**
- **The overall magnitude is 1- 2 arc-second/second.**
- **The dominant response frequencies (italicized values represents the largest contributor) about the HST axes with the <u>+V3 axis oriented toward the sun</u> are:**
  - **VI: *0.096- 0.10*, 0.115, 0.15, 0.34, 0.38, 1.3- 1.4, 3.2 Hz**
  - **V2: *0.10*, 0.98- 1.0 Hz**
  - **VI 0.096- 0.105, 0.34, 0.37- 0.39, *0.60-0.63*, 0.65, 3. Hz**
- **Response with respect to Solar Array orientation varies, with the 0. 1 Hz frequencies about the V1 and V3 axes the most sensitive.**
- **The overall rotational response magnitude is predicted to be 2 to 3 orders of magnitude over budget.**

HST POST DEPLOYMENT
ORBITAL DAY ANOMALY CHARACTERISTICS

- These events occur at seemingly arbitrary times, mostly during the first part of the orbital day.
- The overall magnitudes are less than for the transitions to day and night, but are still on the order of 1 arc-second/second.
- Spectral analysis of these events is currently very limited, although they seem to exhibit the same low frequency characteristics.
- The directionality, build up, and decay response characteristics are not the same as for the transition anomalies. In fact there appears to be at least four different types of response signatures for the early day anomalies.
- The overall rotational response magnitude for these events is predicted to be 2 orders of magnitude over budget.

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SOLAR ARRAY CHARACTERISTICS

- **The Solar Arrays have several modes in the frequency region under question, with the lower bound for its fundamental analytical frequencies at 0.086 and 0.087 Hz.**
- **The nominal frequencies for the first modes, as reported by ESA, are in the 0.190 to 0.95 Hz region.**
- **The Solar Arrays respond directly to the arrival and departure of the sun via changes in thermal gradients on the bi- stems, blankets and spreader bars.**
- **The bi-stems can have pseudo- static tip deflections of 10 to 20 inches over the course of one minute due to changes in the thermal gradient.**
- **Motions at the tip of the array of only 0.5 inches while oscillating in its fundamental modes can cause the observed HST rotation rates.**
- **The observed rotations of the HST change in direct correlation to changes in Solar Array orientation:**
  - **The rotation about the V1 axis shifts to rotation about the V3 axis as the Solar Arrays rotate from being parallel to the V1 axis to parallel to the V3 axis,**
  - **The rotation about the V2 axis is constant and at a different frequency than the V1 - V3 rotation.**
  - **This information coincides exactly with the character of the first two Solar Array modes.**

IDENTIFICATION OF PROBABLE MECHANISMS OF THE ANOMALIES

- **Solar Array geometry studied for potential sources of excitation.**
- **Telemetry data studied for vehicle response characteristics.**
- **Solar Array models used to simulate possible mechanisms.**
  - **Static analysis (thermal deflection, modal gains, etc.).**
  - **Dynamic Analysis (different transient inputs, frequency & damping variations).**
- **Review of NASA direct video tape.**

KEY FEATURES OF THE SOLAR ARRAY

- **Particular portions of the Solar Array geometry are key to understanding the possible mechanisms of disturbance:**
  - **The base of the blanket and the bi-stems are offset from one another by 1.6 inches. This offset is such that with tension in the blanket, the positive array on the +V2 side and the negative array on the -V2 side will have their bi-stem tips pulled toward the sun. The other arrays will be pulled away from the sun.**
  - **The bi-stems on the positive array on the +V2 side and the negative array on the - V2 side have their slots, exposing the inner sleeve, oriented towards the sun. The other arrays have the slots oriented away from the sun and will therefore have greater thermal gradients across their diameter.**
  - **The bistems have an arbitrary initial radius of curvature due to manufacturing of 443 meters or greater.**
- **Some thermal characteristics are also of particular importance:**
  - **At sunrise/sunset, thermal gradients across the diameter of the bi- stem can increase/ decrease by 50.0 F in 50 seconds. (Analyses by LMMS and Hughes agree with this estimate)**
  - **Overall temperature increases on the bi- stem are on the order of 300.0 F and occur over a period of 35 minutes.**
  - **The temperature increases on the blanket are on the order of 150.0 F over the same 35 minute time span.**

CURVATURE CHANGES OF THE ARRAYS

- **The two arrays which have their bistem tips pointed toward the sun, ignoring any thermal loading, will have a tip deflection of 1 or 2 inches, due to the blanket tension.**
- **When the thermal loading is applied, the bistems will tend to bow away from the sun. With a 50 F gradient the bi-stems will tend to deflect the tips on the order of 10 inches.**
- **With the addition of the blanket tension, the ESA analysis indicates that the blankets will add another 5 inches of deflection,**
- **These distortions may not occur symmetrically on a pair of bi-stems for a given blanket, in time or in overall magnitude.**
- **Distortions will be unequal for each pair of blankets on each wing because of the bi- stem slot orientation with respect to the sun.**
- **This allows for three different types of dynamic excitation:**
  - **Dynamic overshoot. The curvature may not occur pseudo- statically. The 50 second build up may allow for some energy to bleed off into the 0.1 Hz mode. A dynamic response of 0.5- 1.0 inches is all that is required.**
  - **Out of phase growth. If one bi-stem defects faster than the other, then a torsion response may develop as one bi- stern pulls on the other through the spreader bar.**
  - **Different tip deflections. If the final tip deflections differ on the two bistems, then the spreader bar could become misaligned on the compensator rails. The misalignment has to be only large enough to cause a stick- slip phenomenon on the rails.**

CROSS-OVER

- As stated previously, two sets of the bi- stems initially have a curvature towards the sun, after sunrise these bi- stems will deflect away from the sun, thus changing its curvature to one away from the sun.
- After sunset these bi- stems will want to revert back to their initial state without the effects of a thermal gradient.
- ESA's analysis did this by subtracting off the temperature induced curvature from the effective curvature which contained the nonlinearity due to the blanket tension. What they did not take into account is that the nonlinear effect will also change and should be recomputed. If this is done they should find either only one stable point which is the one with the tip pointed toward the sun or two stable points in which the second still has the curvature away from the sun but much closer to the neutral point.
- If one set of the bi- stems is crossing over at the Day/Night transitions, that extra "whip" during the cross- over, especially if it is unsymmetrical, could cause added non- symmetry in the residual motions. This is not considered a primary cause, but could add to the response.
- Engineers at Hughes have confirmed that bistem cross-over does happen, but their data have indicated a smooth transition.

WARPING

- If the bi- stems have different temperature gradients across them due to differing fitness tolerances, then the bi- stems will have different tip deflections.
- If the bi- stems have different fields of view of the sun (i.e. vehicle shading or reflections), they will have different tip deflections.
- If one of the two bi-stems twists, it will have a different thermal gradient, and thus they will have different tip deflections.
- This differing in tip deflections could cause the spreader bar or its tension tape to temporarily bind up causing a stick slip phenomenon
- This phenomenon could be induced, not by thermal gradients, but by overall temperature increases. As the bi-stem temperature increases by 250- 300 F, the bi- stems will want to grow independently by 0.4 inches while the spreader bar will want to keep a constant and uniform tension across the top of the blanket.
- While this growth is occurring, if the spreader bar is temporarily pulled with one bi-stem and then released, it could induce the force necessary to cause the response.

AXIAL THERMAL CREAK

- As the bi-stems warm up they will grow about 0.4 inches axially.
- If the growth of the two sleeves on a bi-stem is uneven, then the two sleeves will want to move relative to one another.
- This can induce a stick- slip phenomenon.
- However, the level seem to be quite low and would be mainly in the axial direction.
- This is not considered a likely source for the disturbances.

BI-STEM CASSETTE

- **Concerns regarding thermal effects on the bi-stem cassettes were investigated as a possible source of disturbances.**
- **As the cassette warms up during the daylight portion of the orbit, the remaining bi- stem in the cassette will want to expand.**
- **Creaks involving the axial expansion of the tape still coiled in the cassette could produce moments and forces.**
- **The likelihood of this mechanism being able to produce the observed responses was investigated and found not to produce significant force nor moments to cause the observed responses.**

SOLAR ARRAY DRUM

- As the Solar Array blankets expand and contract, the S. A. drum rotates, pulling in and letting out the blanket to keep constant tension.
- If there is friction in this mechanism, then this could also cause responses on to the HST.
- Simulations of this event show the response but not with the observed spectral character.

NOMINAL THERMAL GRADIENT CHANGES: STATIC ANALYSIS

- Telemetry data indicates that the HST is caused to rotate on the order of I arc- second per second at 0. 1 Hz during the transition events. During this time the Reaction Wheel Assemblies (RWA's) output from 0.2 to 0.8 Nm to counteract this motion.
- A 0.5 Nm torque can be induced at the Solar Array/HST interface by application of a quasi static tip deflection of a solar array of approximately 10 inches.
  - A purely static torque of 5.0 Nm is developed, and a 10% dynamic overshoot is assumed.
  - This dynamic overshoot ratio is in basic agreement with statements made by ESA.
  - Additionally, this dynamic overshoot would tend to oscillate at the fundamental Solar Array frequencies, 0. 1 Hz.
- A 10 inch tip deflection can be caused by the application of a 50.0 F thermal gradient across the bi-stems.
  - Analyses performed by the LMMS thermal dynamics group shows that the bi- stems will acquire about a 50.0 F thermal gradient while exposed to the sun.
- Therefore, a static analysis of the event clearly shows that the Solar Arrays can develop a torque on the HST equivalent to that required by the HST to counteract the anomaly.

THERMAL EXCITATION ANALYSIS RESULTS

- A summary of the BAe analysis for the thermal excitation of the solar arrays is contained in TN- SA- B 142, "The Analysis of the Deployed S.T.S.A.", section 6.1 1.
- The methodology of the analysis appears to be proper, however the assumed values for the input variables are very crucial to the final answer:
  - The thermal gradient was assumed to build up over a 300 second period.
  - Because of the assumed 300 second build up period and the fundamental mode period of 10 seconds, it was assumed that all the solar array blankets would deflect in almost perfect symmetry and thus cancel each others torque induced into the HST. This led to a scaling factor of 0.1 of the effective inertia.
  - The peak thermal gradient used by BAe is 23.20 C.
- A review of these assumptions has led to the following:
  - The LMMS thermal dynamics group analysis indicates a 50- 60 second build up period. This factor has a squaring effect in the solution, thus it will alter the final torque value by a factor of 25 to 36. Predictions by Hughes confirms this build up period.
  - Due to the decrease in thermal gradient build up time, the non- symmetry in the gradients, and the strong likelihood of different Solar Array natural frequencies for each Solar Array, the effective inertia scaling factor should be removed.
  - The LMMS predicted gradient is approximately 28.0 C, depending on bi-stem interface contact.
- The bottom line is that the BAe induced torque prediction of 0.00067 Nm is increased by a factor of 300 to a level of 0.2 Nm, a level consistent with the telemetry and the LMMS static analysis.

ASSESSMENT OF TELEMETRY DATA
SOLAR ARRAY AVERAGE FREQUENCIES

- **Since the Solar Arrays have been identified- as the source of the low frequency responses, several factors concerning the "as built" Solar Array design may be deduced from the available telemetry.**

- **The fundamental "average" frequency (in Hz) of the Solar Arrays:**

SA Mode	Model Frequency	Tran. To Day Freq. (Hz)	Nominal Day Freq. (Hz)	Tran to Night Freq. (Hz)	Nominal Night Freq. (Hz)
1st Bending	0.087	0.106	0.114	0.099	0.113
1st Torsional	0.086	0.110-0.115	0.120	0.103	0.104-0.110

- **The Solar Arrays vary in natural frequency throughout the orbit. The most likely cause is geometrical changes in the Solar Arrays due to the thermal gradient and temperature changes.**

ASSESSMENT OF TELEMETRY DATA
INDIVIDUAL SOLAR ARRAY WING FREQUENCIES

- There is a difference in frequency between the two Solar Arrays, this is indicated by the beating response seen during some of the time periods:
- The first bending mode response, during transition to day, has a beat period of 80 seconds, this indicates a frequency separation of 0.0 13 Hz. Thus, during the daytime transition, one
- Solar Array has the first bending mode at 0. 100 Hz and the other has it at 0. 1 12 Hz.
- The first torsion mode response, during one transition to day, has a beat of 160 seconds, this indicates a frequency separation of 0.006 Hz. Thus, during the daytime transition, one Solar Array has the first bending mode at 0. 107 Hz and the other has it at 0. 1 13 Hz.
- The beating is not "pure" in that the response at the minimums do not drop to zero, this indicates that one wing is responding more than the other.
- The fundamental "individual" frequencies (in Hz) of the Solar Arrays:

SA Mode	Model Frequency	Tran. To Day Freq. (Hz)	Nominal Day Freq. (Hz)	Tran to Night Freq. (Hz)	Nominal Night Freq. (Hz)
1st Bending	0.087	0.100	0.114	0.093	0.113
1st Bending	0.087	0.112	0.124	0.105	0.113 (?)
!st Torsion	0.086	0.113-0.112	0.121	0.098	0.098
1st Torsion	0.086	0.107-0.119	0.114-0.128	0.105-0.110	0.110

- The two Solar Array wings have different frequencies and appear to have different frequency changes.

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ASSESSMENT OF TELEMETRY DATA
SOLAR ARRAY DAMPING

- **During some of the daytime responses, there is evidence of single sinusoid free decay. This information can be used to approximate the effective modal damping using the logarithmic decrement.**
  - **The 1st bending mode has 2.8% modal damping.**
  - **The 1st torsion mode has 1.6% modal damping.**
- **The control system is estimated to be contributing very little to the modal damping. Thus, the actual structurally induced modal damping is close to the measured values, but may be as low as 1.0% based on some other limited measurements.**
- **This is only an approximation for the responses seen during the day. The values can vary depending on initial response amplitude and the observed natural frequency changes with respect to orbital position**
- **No appreciable damping variations were noted for Day vs. Night.**
- **Other modes, though not as clearly evident, do appear in the responses and also exhibit indications of different frequencies for each array and for each period in the orbit.**

NOMINAL THERMAL GRADIENT CHANGES: DYNAMIC ANALYSIS

- **An analysis using the HST model with deployed Solar Arrays was performed:**
  - **A force at the tip of the bi- stems equivalent to the thermal gradient was applied.**
  - **The loading was incremented from 0. to 0.2 lbs over a 60 second period using a 1/4 sine profile and a 1 - cos(ωt) profile. The 0.2 lb loading was used to achieve a 10 inch final tip deflection**
  - **Several different loading cases were evaluated:**
    - » **One solar array blanket.**
    - » **All four blankets with symmetric loading.**
    - » **All four blankets with the individual loading slightly out of phase with respect to time.**
    - » **Loading the upper and lower blankets differently, depending on the orientation of the exposed bi-stem slots.**
    - » **The above analyses with the two Solar Array wings having a nominal 6- 1 1 % difference in their natural frequencies.**

NOMINAL THERMAL GRADIENT CHANGES: DYNAMIC ANALYSIS RESULTS

- The analysis showed the HST responding with the following specifics:
  - For all cases the bi- stem tips oscillated at the fundamental Solar Array frequencies with a peak to peak displacement of 0.2- 1.0 inches.
  - The HST rotational rates about the V2 and V3 axes oscillated at the fundamental Solar Array frequencies with a max rate of 1.- 1.5 arc-seconds/second.
  - With the frequency shifting included, the V2 rotational response exhibited the characteristic build up of response over several cycles that has been observed in most of the Day/Night transients.
- While these are only open-loop computer analyses of the event, it demonstrates that the nominal thermal gradient build up/release at orbital Day/Night transition is the cause of the anomalies observed at those times.
- Further analyses utilizing a closed loop control system have also been performed to develop gain changes/control loop modifications which will minimize the effect.

HST POST DEPLOYMENT ANOMALY CONCLUSIONS

- Based on this analysis, the fundamental solar array modes are the only significant contributor to the observed events.
- The source of the excitation must be occurring on the solar arrays for the Day/Night transitions.
- The solar arrays are the chief suspect in the mid- morning events, although there has been little high data sample rate of the events to investigate.
- The four most likely causes of these events are:

Day/Night

- Residual responses of all four blankets due to the thermal gradient changes at the Day/Night transitions.
- Cross- over of one or two of the blankets due to the thermal gradient changes at the Day/Night transitions, coupled with their tendency to be deflected towards the sun without a gradient.

Daytime

- A warping effect in which a set of stems have different tip deflections and cause a stick- slip phenomenon with the spreader bar.
- Friction in the SA drum causing impulses as the blanket tension is kept constant. This is a mid- morning event if sticking occurs as the drum lets out blanket and a mid- evening event if sticking occurs while the blanket is taken in.

Solar Array Disturbance Characteristics From Feathering Tests EON and EOD Terminator Responses Mid-Day and Mid-Night Responses

SOLAR ARRAY FEATHERING TEST OBJECTIVES

- Hubble Space Telescope (HST) Solar Array Feathering Test (SAFT I and II) were instituted to further gather data and investigate the source of on-orbit disturbances
- The primary objective of the SAFT I and II was to show that the solar arrays are responsible for the attitude disturbance that the HST experiences during the entering of orbital day (EOD), the entering of orbital night (EON), the daytime (Mid-Day), and the night time (Mid-Night).
- A second objective of the SAFT II was to gather flight data for verification of a stick-slip model that ESA is using to simulate the on-orbit behavior of the solar arrays.
- Data herein represents a qualitative assessment of each solar array in order to better characterize the stick-slip phenomena for inclusion in the ESA on-orbit simulation.

ENTERING ORBITAL DAY (EOD) DISTURBANCES FEATHERING TEST COMPARISONS

- The EOD terminator response for the nominal configuration (both SAs oriented at 90 degrees) has a duration of 5 to 6 minutes
  - The responses recorded during this test are consistent with data analyzed between July and September of 1990. (Post HST Deployment)
  - The V1 axis shows the classical thermal gradient ramp, while the V3 axis exhibits multiple small pulses of energy during this time frame. Responses on both axes are dominated by a 0.1 Hz. Response, the dominant out-of-plane SA frequency.
- The -V2 feathering case shows the duration of the EOD event to have the same duration as the nominal case.
  - The amplitude of the V1 response is less than the V1 response recorded for the nominal case. However, the V3 axis for this case shows the same pulsing phenomena observed for the nominal case about this axis.
- The +V2 feathering case results show the same phenomena previously observed for both the -V2 wing feathering and the nominal configurations. The peak rate about the V1 axis is the lowest of the three cases. The duration of the EOD for this case is again 5 to 6 minutes.
- The EOD for the case with both arrays feathered show a dramatic decrease in peak amplitude about the V1 axis. The response about the V2 axis is comparable to the responses measured about this axis for the other feathering cases.
- The effect of feathering the -V2 array appears to have no significant effect on the response of the vehicle when passing through an EOD terminator.
- However, the feathering of the +V2 array showed a reduction of one order of magnitude in the 0.1 Hz. response when compared to the +V2 feathering case and the nominal case.

V1 EOD RATE RESPONSE

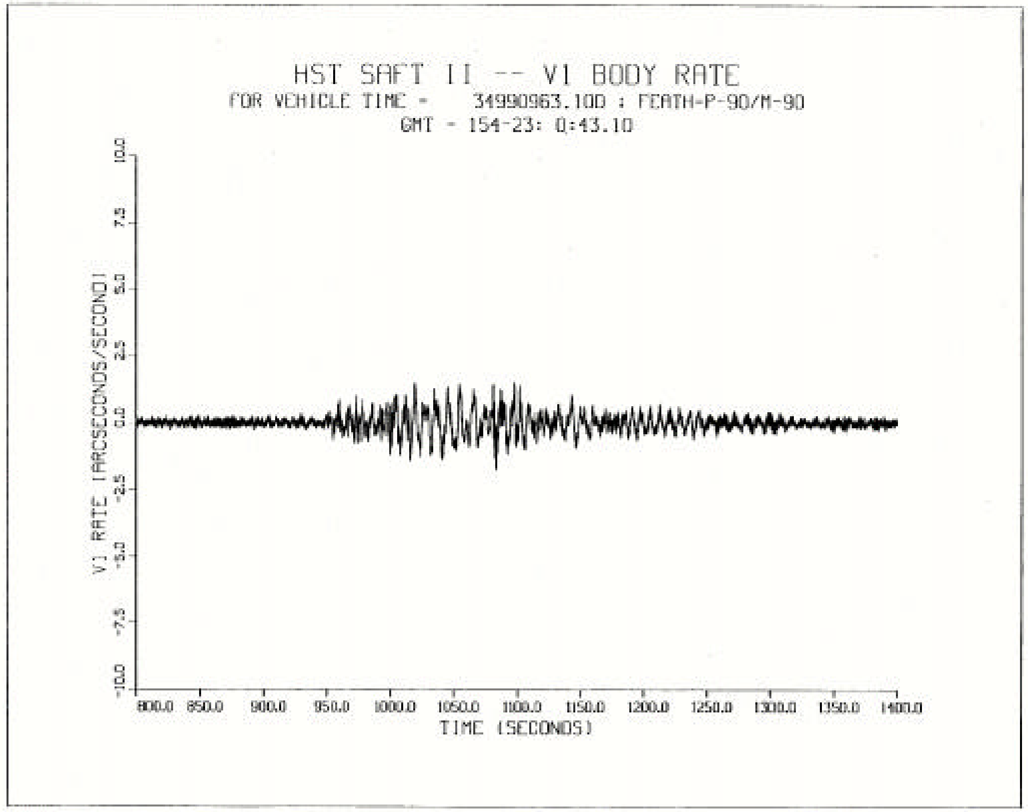

Figure 16. V1 Rate Response at EOD (Nominal)

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V2 EOD RATE RESPONSE

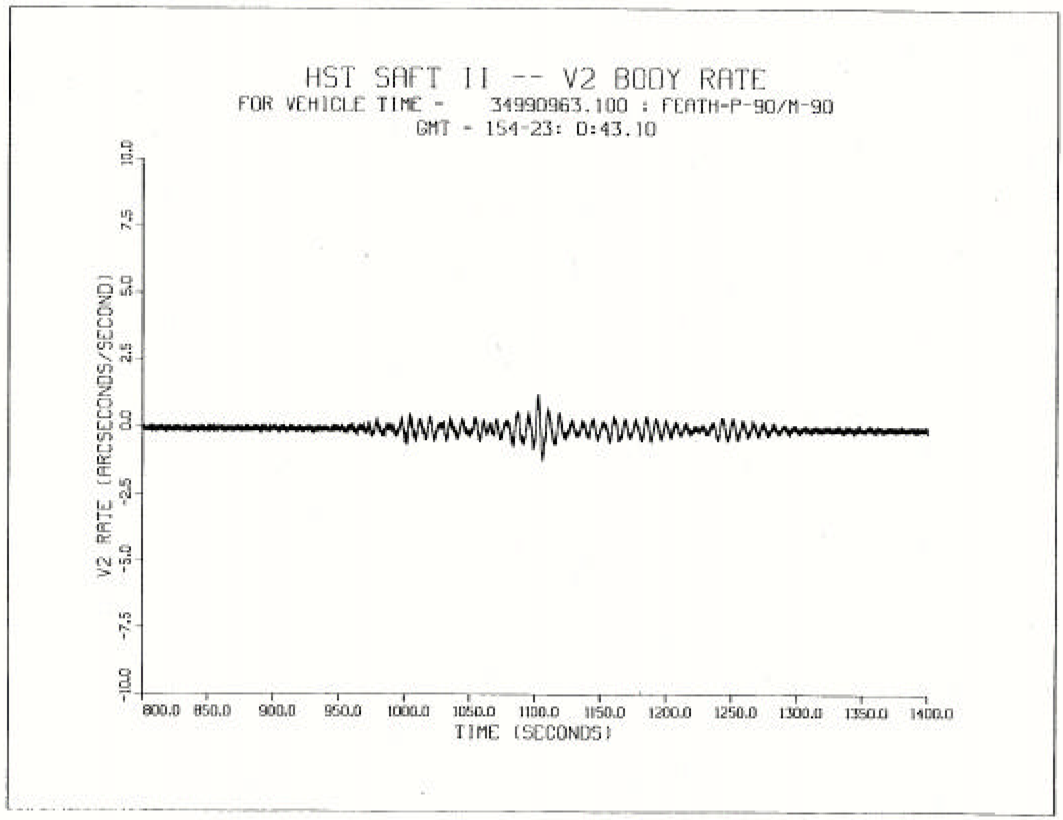

Figure 17. V2 Rate Response at EOD (Nominal)

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V3 EOD RATE RESPONSE

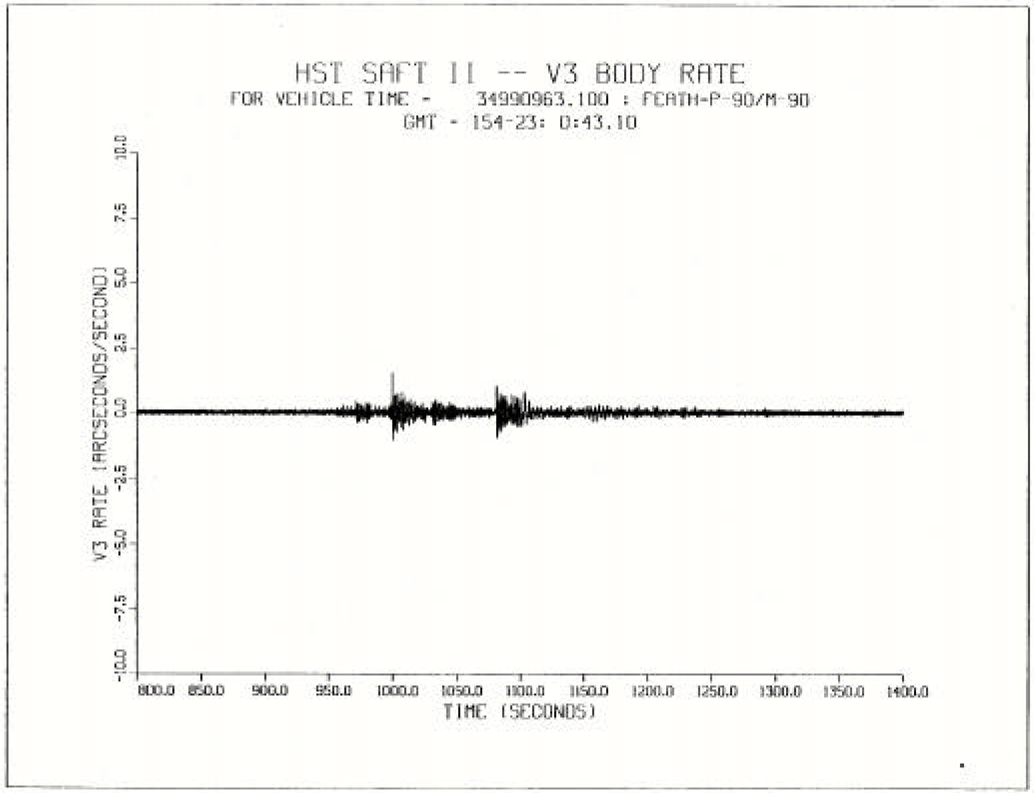

Figure 18. V3 Rate Response at EOD (Nominal)

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MID-DAY DISTURBANCE FEATHERING TEST COMPARISONS

- **The mid-day disturbances response characteristics recorded for the solar arrays at 90 degrees correlate to previous analyses and trend summaries.**
- **The effect of feathering the -V2 array exhibited a beating disturbance on both the V1 and the V3 axes prior to the EON terminator. This disturbance was apparent during the entire orbital day.**
- **The +V2 feathering test revealed mid-day disturbances similar in characteristic to those seen with the arrays at their nominal position.**
  - **However, the first mid-day disturbance shows response levels higher than those seen in the nominal position. The reason for such high responses could be due to the fact that the +V2 array was slewed to its feathered position prior to the disturbance and residual undamped oscillations of the array contributed to the overall response before the array settled.**
- **The disturbances recorded for the case with both arrays feathered occurred within 6 minutes of each other and approximately 20 minutes after the arrays were commanded to their feathered position. Their character is similar to response reported in other cases.**
  - **The mid-day disturbances reported with both arrays feathered exhibited the similar impulse response observed in other mid-day disturbances but did not have the distinct single DOF decay associated with it.**
  - **The same pulsing phenomena observed for the -V2 feathering case is seen about the V1 and V3 axes for this case leading up to the mid-day disturbance and continuing up to the EON terminator.**
  - **The time that these responses occurred were less than 30 minutes after the Vehicle slewed both arrays to 0 degrees.**
- **It is apparent that there is some repeatability between the high frequency responses and the 0.1 Hz. responses, but nothing suggests that these responses are being forced to be periodic.**
- **However, the damping characteristics for all responses vary without any direct correlation to one another.**

V1 MID-DAY DISTURBANCE RATE

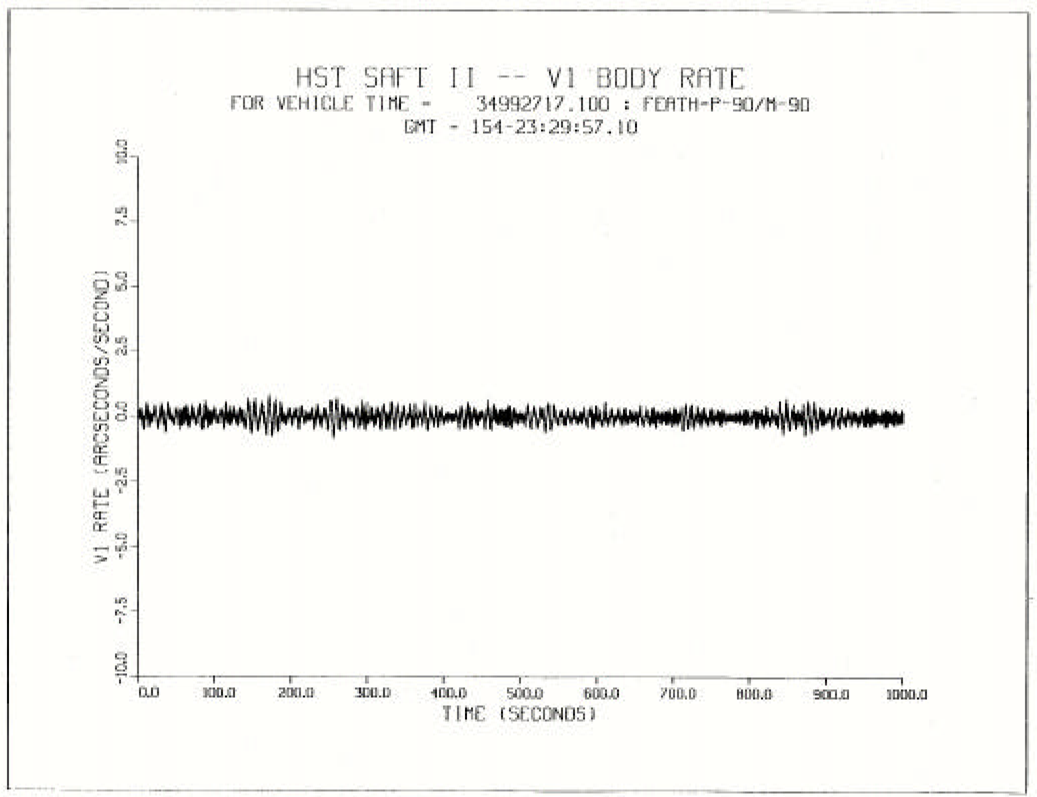

Figure 21. V1 Rate Response at Mid-Day (Nominal)

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V2 MID-DAY DISTURBANCE RATE

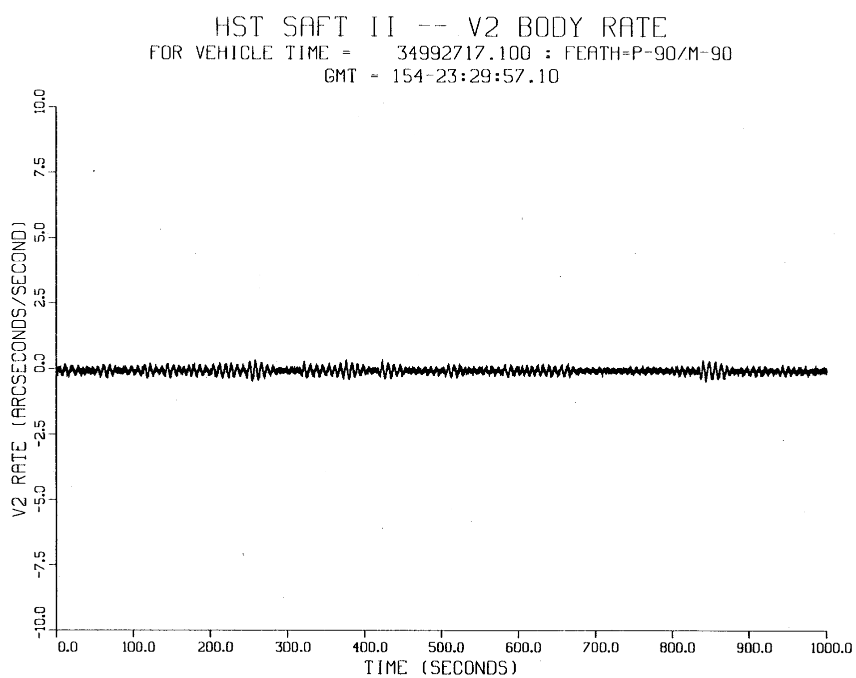

Figure 23. V2 Rate Response at Mid-Day (Nominal)

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V3 MID-DAY DISTURBANCE RATE

Figure 25. V3 Rate Response at Mid-Day (Nominal)

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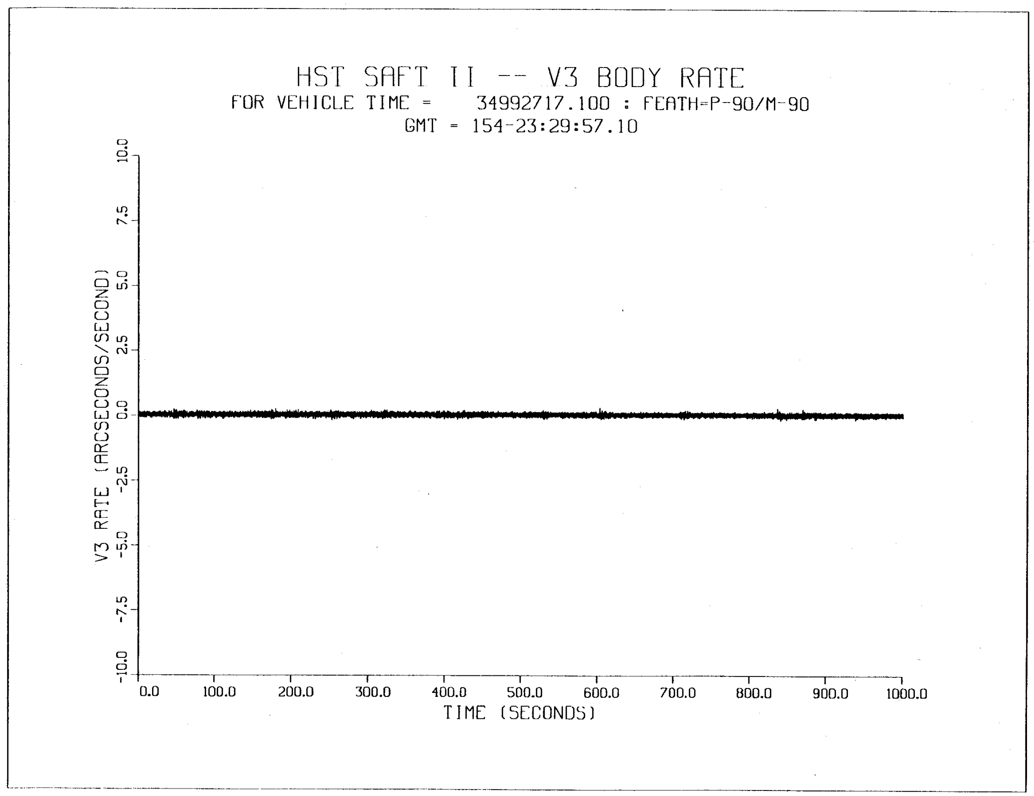

END OF NIGHT (EON) DISTURBANCE FEATHERING TEST COMPARISONS

- The EON terminator responses for all feathering cases typically have the same duration. The duration of this terminator is 3 to 5 minutes which is similar to that of the EOD terminator.
  - Rate values show that the measured rates about each vehicle axis are comparable to one another for the four primary feathering cases.
- The same frequency response trend observed in the EOD terminator for the nominal case and both cases with one wing feathered has been observed.
- The 0.1 Hz. response for the +V2 feathering case is 6 times less than the -V2 feathering case and 10 times less than the nominal case about the V1 axis.
- The same conclusion drawn for the EOD terminator can be drawn here. The effect of feathering one array does not have a significant effect on reducing the rates seen during this terminator. Both arrays are seen contributing equally to the disturbance during this terminator.

V1 EON DISTURBANCE RATE

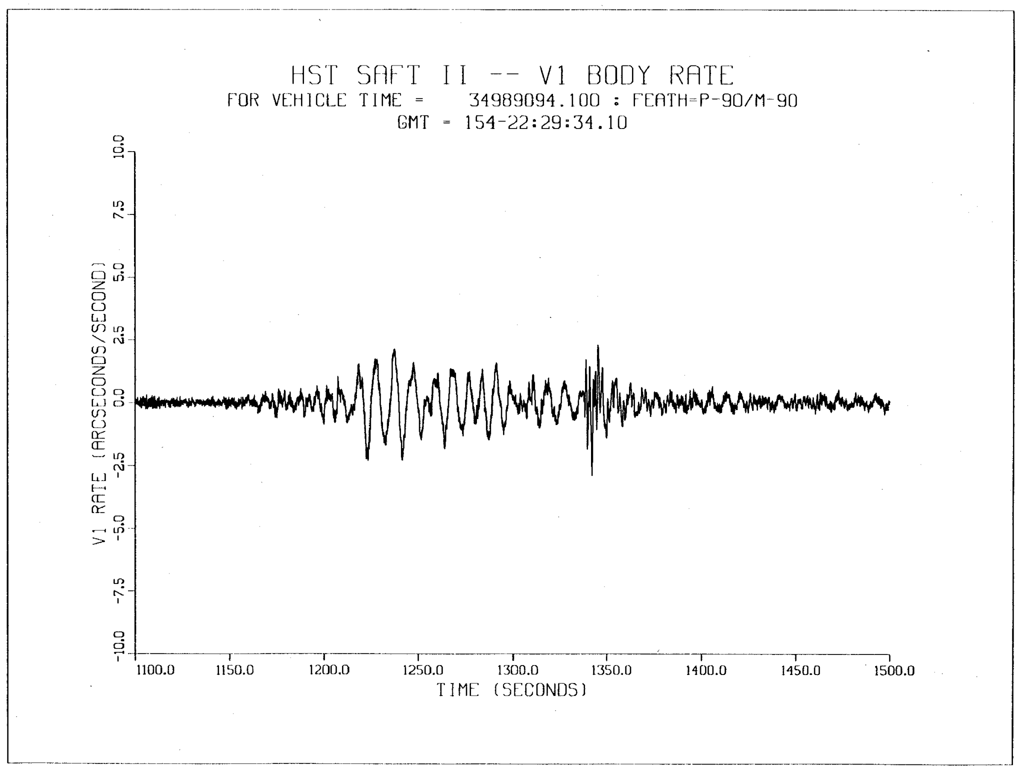

Figure 1. V1 Rate Response at EON (Nominal)

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V2 EON DISTURBANCE RATE

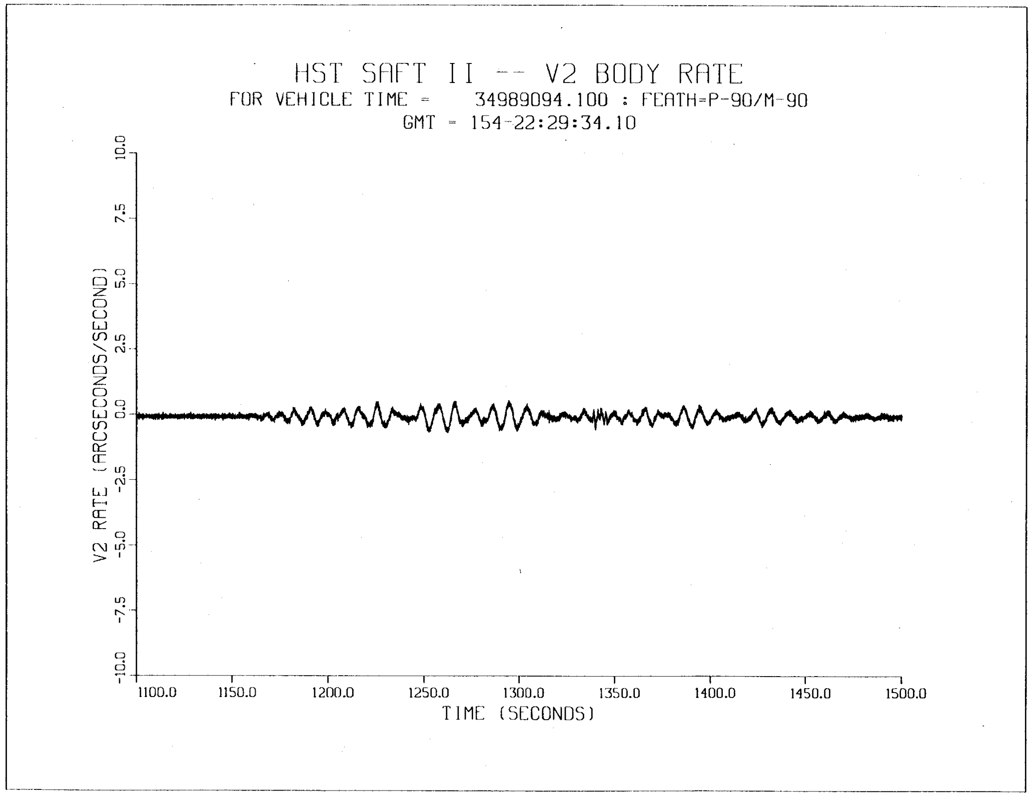

Figure 2. V2 Rate Response at EON (Nominal)

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V3 EON DISTURBANCE RATE

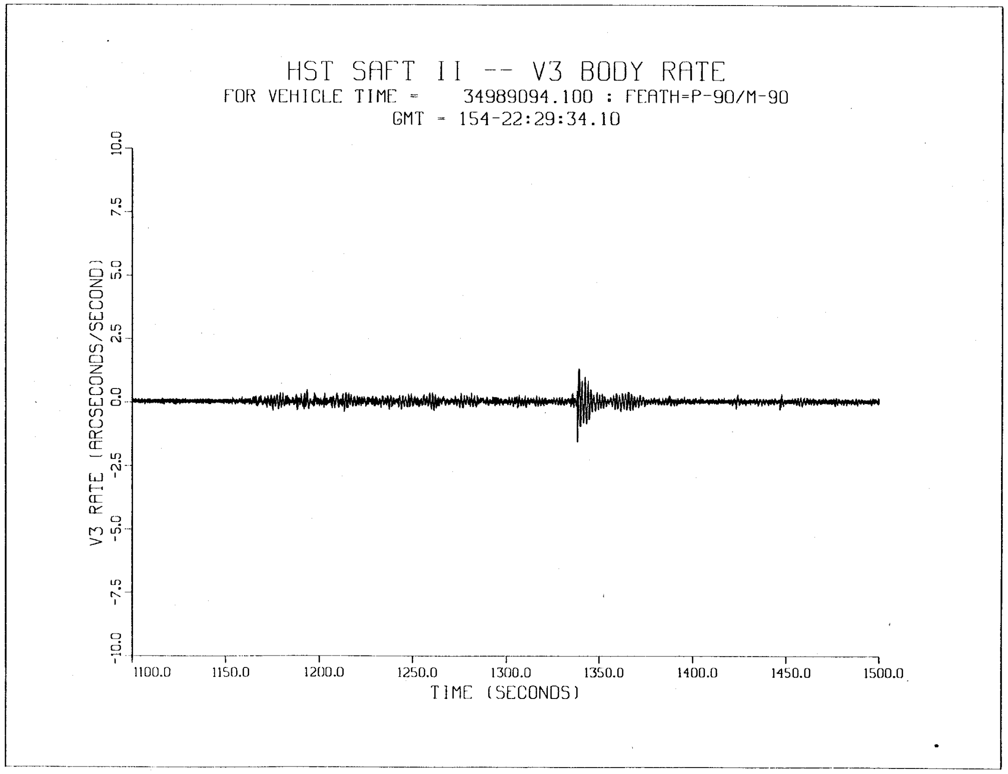

Figure 3. V3 Rate Response at EON (Nominal)

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MID-NIGHT DISTURBANCE FEATHERING TEST COMPARISONS

- The mid-night disturbance has been characterized as a single high frequency response pulse with response components about the V1 and V3 axes.
- Three different mid-night disturbances were observed for the nominal configuration. All three events occurred within 20 minutes after the EON terminator and are consistent with the mid-night disturbance characterization from early mission life.
- Two mid-night disturbances were observed during the -V2 feathering portion of the test.
  - The response was characteristic of the early mission responses and are dominated by a 0.12 Hz. response primarily about the V1 axis and a 0.65 Hz. response dominant about the V3 axis.
  - This indicates that the +V2 wing is being excited either thermally or by some stick/slip phenomena and is inducing enough motion to excite the in-plane motion of the -V2 array.
  - The second event for this case shows a high frequency pulse about the V1 axis followed by another larger high frequency pulse with a single DOF decay into a low frequency motion.
  - The high frequency pulse is at 0.6 Hz. while the low frequency motion is at 0.1 Hz. The 0.65 Hz response dominates both V1 and V3 axes with higher amplitudes evident about the V1 axis. This suggests that the in-plane motion of both arrays are being excited.
- A mid-night disturbance was observed primarily about the V3 axis during the +V2 feathering case.
  - The response noted for this disturbance does not follow the character observed during the nominal configuration nor the -V2 feathering case. These cases had distinct responses about both the V1 and V3 axes whereas this case's response is solely about the V3 axis.
  - The frequency response for this event shows a 0.62 Hz. response dominating the V3 axis This response suggests that this is the in-plane motion of the +V2 array.
- The case with both arrays feathered showed a mid-night disturbance occurring toward the conclusion of the test. The response recorded correlates to patterns in the previously discussed tests. Both the V1 and V3 axes have strong 0.65 Hz. and 0.73 Hz. responses. This response about both axes shows that both arrays are moving in-plane.

V1 MID-NIGHT DISTURBANCE RATE

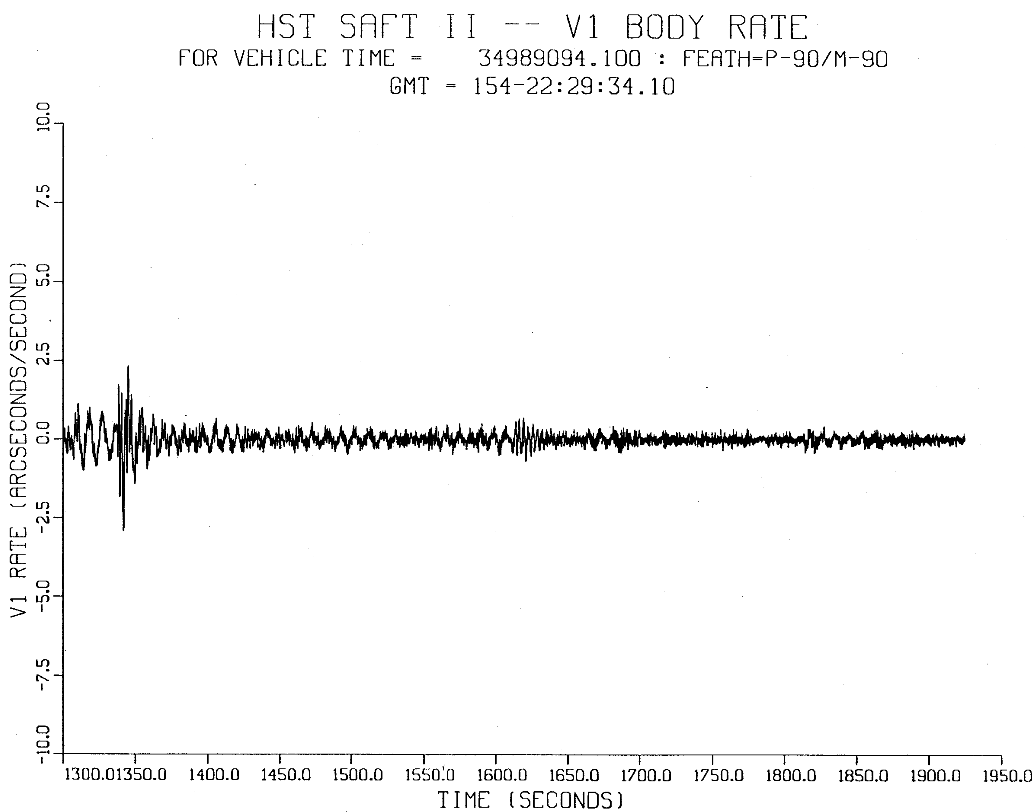

Figure 6. V1 Rate Response at Mid-Night (Nominal)

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V2 MID-NIGHT DISTURBANCE RATE

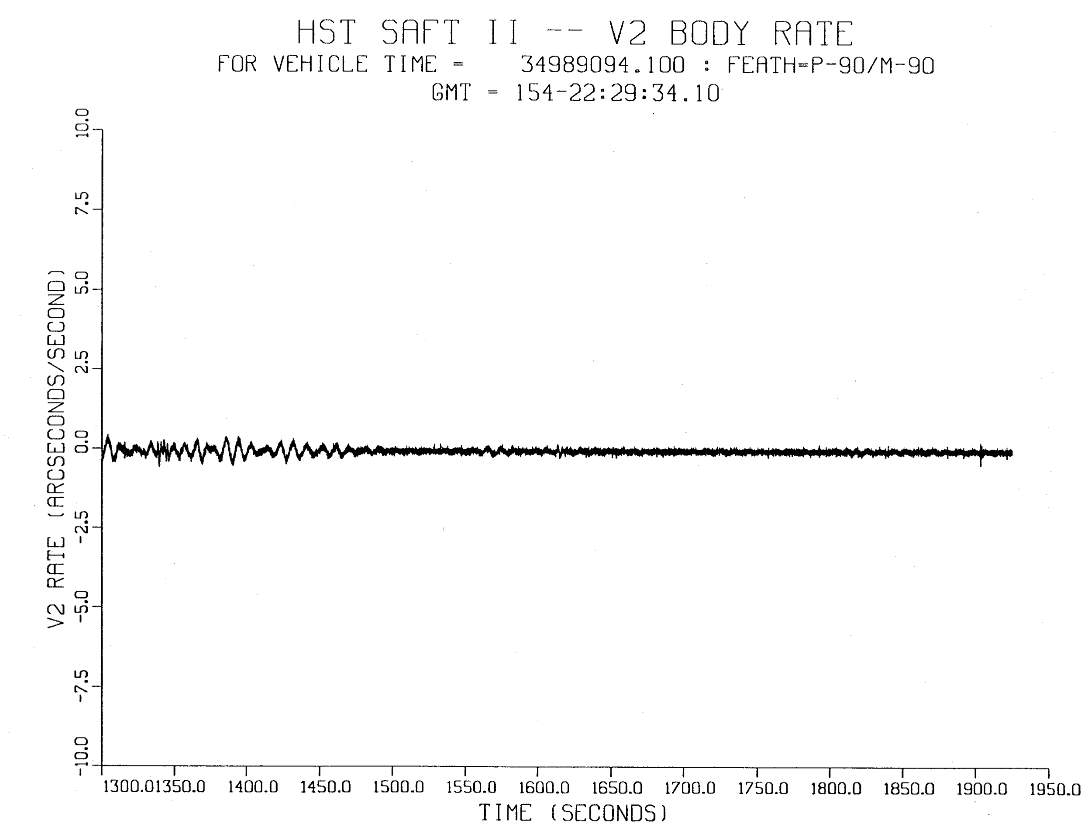

Figure 7. V1 Rate Response at Mid-Night (Nominal)

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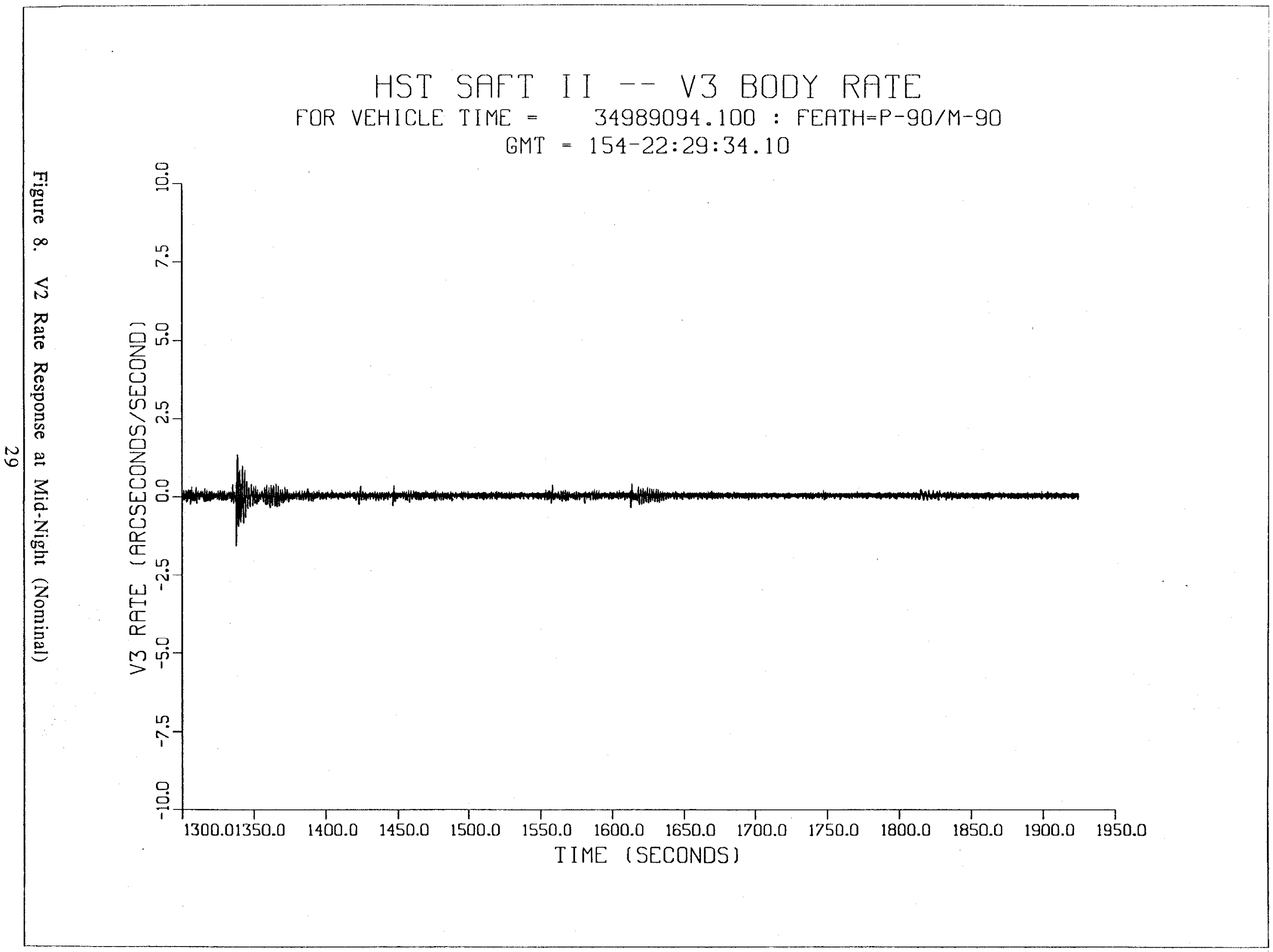
V3 MID-NIGHT DISTURBANCE RATE



FEATHERING TEST CONCLUSIONS

- The data from all tests conclusively showed that the solar arrays were the primary source of the external disturbances described:
  - With both arrays feathered edge on to the sun and allowing time for thermal stabilization, the large rate disturbances were virtually non-existent.
  - The data also showed that each array contributed equally to the EOD and EON disturbances, but the large mid-day and mid-night disturbances are caused by each array separately.

- The data recorded during this test was consistent with previous disturbance assessments in that the 0.1 Hz. response dominated the EON and EOD terminators, while the 0.6 Hz. response was much stronger during the mid-day disturbances.
  - The source of the terminator disturbances has not been altered by this investigation and is due to the thermal gradient across the bi-stems with some evidence of stick-slip friction possibly caused by the spreader bar.
  - The mid-day disturbances are still assumed to be induced by a stick/slip friction phenomenon.

- Jitter estimates show that with both wings feathered a significant decrease in V1 jitter is achieved.
  - However, calculations of V2-V3 RSS RMS jitter for each SA orientation show that there is not a significant improvement in jitter when both wings are feathered or when one wing is feathered.
  - One reason for the V2-V3 jitter levels with both wings feathered is comparable to other orientations is that the 0.1 Hz. response has now shifted from the V1 axis to the V3 axis, thus decreasing jitter about the V1 axis and increasing jitter about the V3 axis.

On-Orbit Jitter Test

HST ON-ORBIT JITTER TEST

- **The objective of the HST HSP optical jitter test was to provide pitch and yaw frequency and jitter system information at a high sampled data rate measured at the HST focal plane.**
- **The HSP was selected as the measurement sensor since it is capable of sampling information at 1000 Hz.**
- **The HSP measures optical jitter by placing a bright star image on the edge of the aperture and measuring the resulting flux as the star moves in and out of the aperture.**
- **Four test were performed which each consisted of four segments**
  - **A period where no mechanisms were operating**
  - **A period where tape recorders were commanded on**
  - **A period where the High Resolution Spectrograph was commanded on**
  - **A second period where no mechanisms were operating**
- **Optical jitter and frequency responses are determined by transforming the HSP flux measurements from each test segment to standard measurement values of milli-arcseconds and performing spectral analyses.**
- **Spectral analysis results are compared to ground based modal test results to determine the accuracy of on-orbit models currently in use.**
- **Jitter measurement results are calculated over one and 60 second intervals and compared to spacecraft jitter allocations.**

LOCKHEED MARTIN

HST ON-ORBIT JITTER TEST RESULTS

V2a Test		V2b Test		V3a Test		Prelaunch Prediction *		Average
Freq.	Description	Freq.	Description	Freq.	Description	Freq.	Description	Percentage Difference
(Hertz)		(Hertz)		(Hertz)		(Hertz)		In-orbit vs. Pre-launch
0.40	Solar Array (SA)							
0.55	SA in-plane	0.55	SA in-plane			0.45	SA in-plane	22.22
	bending		bending				bending	
0.65	SA in-plane	0.65	SA in-plane					44.44
	bending		bending					
				1.00	Aperture Door	0.91	Aperture Door	9.89
1.1-1.3	High Gain Antenna	1.1-1.5	HGA	1.30	HGA	1.1-1.3	HGA	5.56
	(HGA)							
		1.70						
		2.10	ESTR	2.10	ESTR			
2.50	ESTR	2.50	ESTR	2.50	ESTR			
		3.00	ESTR	3.00	ESTR			
3.30	ESTR	3.20	ESTR	3.10	ESTR			
13.60	HST Scissors Mode	13.60	HST Scissors Mode			13.60	HST Scissors Mode	0.00
				16.40	Aft Bulkhead	16.10	Aft Bulkhead	1.86
					Drumhead Mode		Drumhead Mode	
		17.20	Aft shroud			17.00	Aft shroud	1.18
21.70	HST SSM			22.10	HST SSM			
	Bending Mode				Bending Mode			
24.50	Metering truss	24.50	Metering truss	25.00	Metering Truss	25.40	Metering Truss	-2.89
57.40	Secondary Mirror	57.40	Secondary Mirror	56.50	Secondary Mirror	55.10	Secondary Mirror	3.63
	Translation		Translation		Translation		Translation	
60.00	Primary Mirror			60.00	Primary Mirror	59.80	Primary Mirror	0.33
	Rotation				Rotation		Rotation	
64.40	ESTR Harmonic	64.50	ESTR Harmonic	64.70	ESTR Harmonic			
		84.50	GHRS Carrousel	84.50	GHRS Carrousel	83.00	GHRS Carrousel	1.81
				94.50	GHRS Carrousel	90.00	GHRS Carrousel	5.00
				113.00	Secondary Mirror			
					Translation			
				116.00	Secondary Mirror	118.00	Secondary Mirror	-1.69
					Translation		Translation	
		123.00	Secondary Mirror			123.00	Secondary Mirror	0.00
			Translation				Translation	
		132.00	Secondary Mirror			131.00	Secondary Mirror	0.76
			Torsion				Torsion	

* The HST Modal Survey Test configuration included a ground support aperture door, test batteries while excluding the SAs, WFPC, and two equipment section doors

HST ON-ORBIT RESPONSE CONCLUSIONS

- HST has been in operation for 9 years.
- Numerous on-orbit tests have been performed in an effort to characterize the Vehicle's dynamics.
  – SA Feathering Tests
  – On-orbit transfer Function Tests
  – On-orbit Jitter Tests using Science Instruments
- All testing consistently shows that the vehicle has consistent dynamic responses and amplitudes from orbit to orbit.
  – Dynamic characterization is currently limited to vehicle rate measurements by the RGAs. No other sensors available.
  – HSP was removed during SM1
  – Percentage of change in frequency response < 5%.
- For all HST ground based modes and frequency, on-orbit data shows that the difference between ground base measurements and on-orbit measurements is < 10%
  – Aperture door response shows a difference of 9.9%.
- Both SAI and SAII show differences between analytically predicted responses and on-orbit response of 45% or less.
  – Both SAI and SAII were never tested in the deployed configuration prior to launch.
  – Could not be supported in 1 g environment
  – Deployment functional tests were performed in a water table using floats to support the array.

HST ON-ORBIT RESPONSE CONCLUSIONS (CONTINUED)

- **Determination of mode shapes on-orbit not feasible nor possible with HST**
  - **239 Accelerometers used to measure mode shapes during HST modal survey**
  - **21 Accelerometers installed to the FGS bench, Primary Mirror, and Secondary Mirror for HST Modal Survey.**
  - **These 21 accelerometers were not removed after the survey and currently are on board HST.**
    - » **Studies have addressed the possibility of using the 21 accelerometers to measure on-orbit jitter**
    - » **It was concluded that the technique to measure on-orbit jitter was to complex, expensive, and does not diagnose for sensor failures**
    - » **It was recommended not to use the fly-away accelerometers and the cable leads were removed prior to flight.**
- **To date, free-flight satellite technology database responses between ground base testing and on-orbit measurements is limited**
  - **All on-orbit measurements are limited to system identification (frequency and damping) using existing spacecraft sensors (primarily gyro telemetry)**
- **HST has the largest on-orbit system identification database of any public domain free-flight satellite.**
  - **Two transfer functions tests completed to identify frequency, damping, and Kb values for low frequency system responses (<3 Hz)**